ELSEVIER

journal homepage: www.elsevier.com/locate/jmatprotec

Pad roughness variation and its effect on material removal profile in ceria-based CMP slurry

Boumyoung Park[a], *Hyunseop Lee*[a], *Kihyun Park*[a], *Hyoungjae Kim*[b], *Haedo Jeong*[c,*]

[a] *Department of Precision & Mechanical Engineering, Pusan National University, Jangjeon-Dong, Geumjeong-Gu, Busan, 609-735, South Korea*
[b] *Busan R&D Center, KITECH, San 30, Jangjeon-Dong, Geumjeong-Gu, Busan, 609-735, South Korea*
[c] *School of Mechanical Engineering, Pusan National University, Jangjeon-Dong, Geumjeong-Gu, Busan, 609-735, South Korea*

ARTICLE INFO

Article history:
Received 21 September 2006
Received in revised form
23 July 2007
Accepted 13 October 2007

Keywords:
Chemical mechanical polishing
Ceria slurry
Pad roughness
Material removal

ABSTRACT

The pad roughness plays a key role in material removal in oxide chemical mechanical polishing (CMP) process. Its variation also has an effect on within wafer non-uniformity. The R_{pk} among roughness parameters, which is related to pad wear characteristics, was investigated to find the correlation between spatial roughness distribution of a polishing pad, and material removal profile in CMP, using two different types of slurries. The removal rate of ceria-based slurry for STI CMP was higher in the wafer center than that of the silica-based slurry. This is because the pad roughness distribution in a convex shape is formed across the pad radius in the contact area between pad and wafer instead of the degradation of pad roughness during CMP. Also, there is an increase of R_{pk} results in the increase of average friction force by comparison with the decrease of friction force in CMP using silica-based slurry. This result may be expected as the effect of the chemical tooth of ceria abrasive and slurry accumulation in the wafer center causes a roughening of the pad surface just as sandpaper.

1. Introduction

Chemical mechanical polishing (CMP) has been widely used for global planarization of multilevel interconnects in the microelectronics industry (Qin et al., 2004). During CMP process, target materials such as oxide (SiO_2), tungsten (W), and copper (Cu) are polished by the contact pressure and sliding motion of the pad, slurry, and wafer (Jin et al., 2005). The material removal depends on numerous variables such as applied pressure, relative velocity between pad and wafer, pad properties (hardness, elastic modulus, pad surface roughness, etc.) and slurry characteristics (abrasive size, abrasive concentration, chemical components, etc.) in CMP process (Oliver, 2004). In regard to the aspect of pad surface roughness, a conditioning process has been performed to remove the debris from the pad surface and restore pad surface quality. The conditioning process is essential to maintain high material removal rate and good within wafer non-uniformity. Pad conditioning may be conducted by using the in situ method; while wafers are being polished, or the ex situ method, either prior to or after the wafers have been polished (Scott Lawing, 2002).

McGrath (MaGrath and Davis, 2004) reported the relationship between pad surface feature degradation and material removal rate by evaluating the deterioration of the pad surface during CMP. Oliver (Oliver et al., 2000) has studied the relationship between pad properties and decline of material removal rate in the absence of conditioning process. The pad surface roughness decreases during polishing because the shearing forces of polishing reduce the height and number of pad asperities. Hooper (Hooper et al., 2002) found the

* Corresponding author. Tel.: +82 51 510 2463; fax: +82 51 518 8442.
E-mail address: hdjeong@pusan.ac.kr (H. Jeong).
0924-0136/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmatprotec.2007.10.033

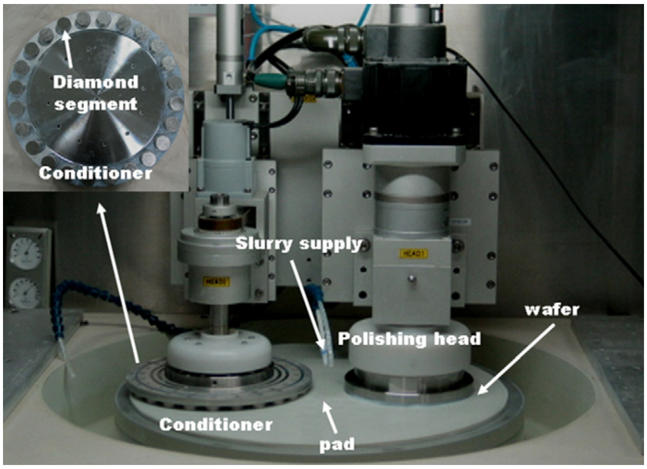

Fig. 1 – CMP equipment (GNP POLI500).

correlation between conditioning density and both geometric wear, and the surface properties of the polishing pad. Yoshida (2004) proposed a practical method to bridge a measured profile of pad asperity in microscopic scale to a set of simple parameters which describe the elastic behavior for CMP process.

Although they reported the relationship between the pad roughness and CMP results, a study on the distribution of pad surface roughness and the removal rate profile induced by slurry types is still insufficient. In detail, different authors have researched the effect of pad roughness on material removal using the slurry with alkali silica (SiO_2)-based abrasives in oxide CMP process. However, the slurry with neutral ceria (CeO_2)-based abrasives has recently been utilized for the removal of silicon dioxide not only in the STI (shallow trench isolation) CMP process, but also in ILD (interlayer dielectric) CMP process because of high planarity performance (Lee et al., 2007). In comparison with silica-based slurry, the material removal behavior of ceria abrasives has a condensation reaction between silanol group and coordinated ceria abrasive surface (Tomozawa, 1997; Cook, 1990). Therefore, Lim (Lim et al., 2005) reported that oxide CMP using ceria-based slurry results in the faster removal rate of the wafer center, which leads to bad non-uniformity over a wafer surface. In this study, non-uniformity was considered from a pad surface roughness view point. Thus, the correlation between material removal rate profile and pad surface roughness was investigated using two types of slurry during oxide CMP, and then we tried to study the mechanism of pad roughness formation of ceria-based slurry.

2. Experiments

Experiments were carried out to investigate the effect of pad roughness variation on material removal profile using R&D GNP POLI500 polisher with a polyurethane pad as shown in Fig. 1. Table 1 describes the experimental conditions. The 4 in. blanket wafer with a thermally grown SiO_2 film was polished at a pressure of 500 g/cm^2 and a rotation velocity of 97 rpm (carrier)/103 rpm (platen). The conditioning process was ex situ at a pressure of 60 g/cm^2 and a rotational velocity of 40 rpm (conditioner disk) and 60 rpm (platen). The different types of slurry were alkali-based slurry with fumed silica abrasives, and a neutral-based slurry with ceria abrasives. The slurry flow rate was kept constant at 150 cc/min.

Table 1 – Process conditions

Parameters	Conditions
Pressure	500 g/cm^2
Velocity	C97/P103 rpm
Oscillation	None
Conditioning	Ex situ
Wafer	Thermal oxide 4 in.
Slurry	Silica-based slurry, ceria-based slurry
Pad	IC1400Nitta-Haas

The pad surface roughness after CMP process was measured by surface roughness tester (Mitutoyo SJ-301). Fig. 2 shows the schematic of the pad surface measurement. The spatial sliding distance of the polishing pad generally has the abnormal feature of parabola according to pad radius as shown in Fig. 2(a), which results in the wear profile of pad surface roughness during CMP. Therefore, any oscillation of polishing head and conditioner was not performed to estimate exactly the effect of the pad roughness variation on the removal rate profile in this experiment. Fig. 2(b) also shows the measuring

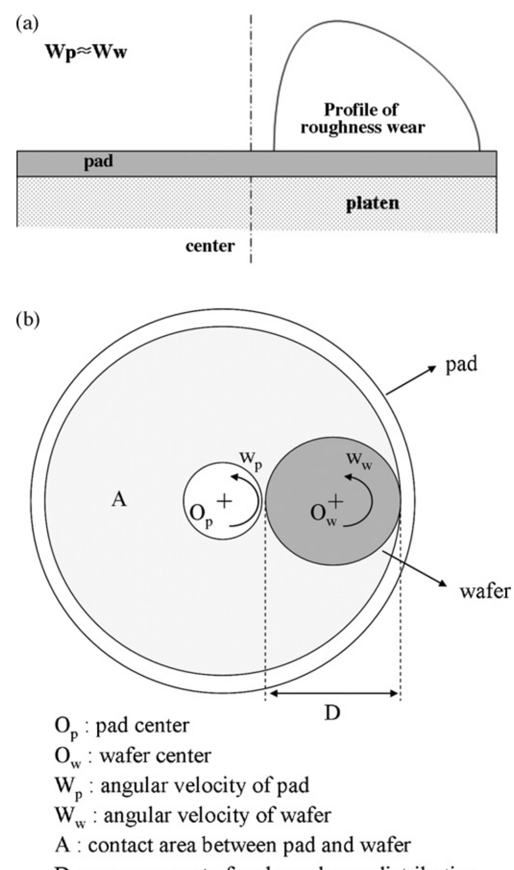

Fig. 2 – Schematic of pad roughness measurement. (a) Spatial sliding distance of pad (pad wear profile). (b) Measurement position of pad roughness.

position of pad roughness, and the pad roughness distribution, which was measured on the contact area between pad and wafer. In particular, "*D*" is the measuring range of pad roughness distribution.

The polisher has a monitoring system which is able to measure the friction force during CMP process. The piezoelectric force sensor was installed for obtaining friction force signals on the back of the polishing head. The signals from the force sensor were amplified through a charge amplifier and then transferred to a data acquisition board (Jeong et al., 2004). The measurement of friction force will help analyzing the polishing results in this study.

3. Results and discussions

3.1. *Pad surface roughness in CMP process*

The conventional polyurethane pad contains randomly distributed pores which is approximately 35% of the total volume (Oliver, 2004; Oliver et al., 2000). Fig. 3(a) shows the pad asperities and the pores on the pad surface. Fig. 3(b) is a three-dimensional image of IC1000™ (made by Rohm & Haas Inc.) measured using a non-contact surface profiler Nanoview™ (made by Nanosystem Inc.). It is certain that the oxide film cannot be polished by a new polyurethane pad, despite high pressure and velocity during oxide CMP process, because it does not have any surface roughness upon the pad asperities to ensure material removal rate. The wear of surface roughness and the phenomenon of pore glazing can also occur during oxide CMP. They may be regenerated by the conditioning process using a disk with diamond grits, thus the rough surface asperities made by conditioning are enough to achieve an effective removal rate.

The parameters of surface roughness can be classified into three types. These are amplitude parameters, spacing parameters and hybrid parameters. R_a, which is the arithmetic mean

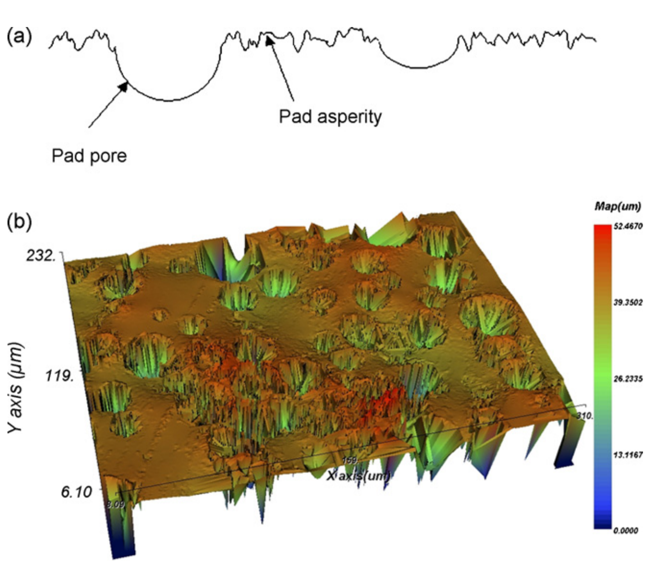

Fig. 3 – Surface image of polyurethane pad. (a) Diagram of cross section of IC1000 (Oliver et al., 2000). (b) Surface image of IC1000.

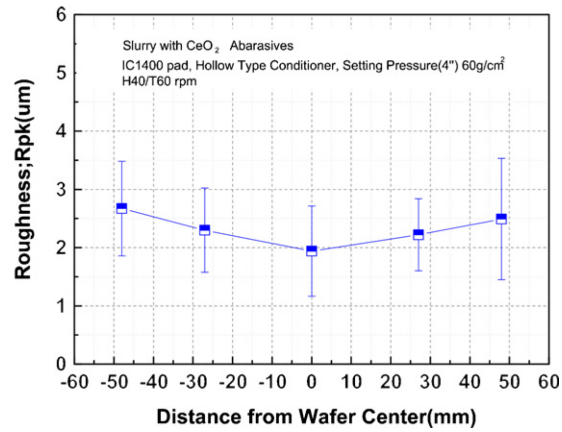

Fig. 4 – R_{pk} value as a function of distance from wafer center after conditioning.

of the absolute values of the profile deviations from the mean line, has widely been used as conventional amplitude parameter in many engineering researches. However, it is impossible to completely describe the pad surface with amplitude parameters. McGrath (MaGrath and Davis, 2004) and Park (Park et al., 2007) both adopted the hybrid parameters for successful description of their works because the amplitude parameters are not sensitive to roughness profile variation or deviation. Therefore, the hybrid parameters were chosen in this study. The hybrid parameters such as R_{pk}, R_k and R_{vk} are suited to explain the roughness changes during CMP process. The reduced peak height, R_{pk}, is an estimate of the peak above the main plateau and is related to the wear characteristics of a polyurethane pad. The core roughness depth, R_k, refers to the depth of the working part of the surface, which carries the load and closely contacts the wafer surface. The reduced valley height, R_{vk}, is an estimate of the depth of the valleys, and is related to the ability of the surface to retain polishing slurry. The R_{pk} must be considered in order to study the influence of pad roughness on material removal, because the R_{pk} is the area of most rapid wear during CMP process (Park et al., 2007; http://www.talyer-hobson.com). Therefore, the authors will focus on the R_{pk} value among hybrid parameters in experiments.

3.2. *Pad roughness variation and removal rate profile of silica-based slurry*

While the pad surface is roughened by a conditioner with diamond segments as shown in Fig. 1, the rotation ratio between conditioner and pad has an influence on pad surface wear. Chang (Chang et al., 2007) indicated that the spatial distribution of sliding distance, according to rotation ratio, induced non-uniform pad wear. Nevertheless, the conditioner oscillated. Fig. 4 shows the R_{pk} distribution after conditioning without oscillation using hollow type conditioner. The initial distribution of pad roughness in the contact area between pad and wafer was a little concave after ex situ conditioning. In general, the surface roughness profile before CMP can affect within wafer non-uniformity for material removal rate. However the formed distribu-

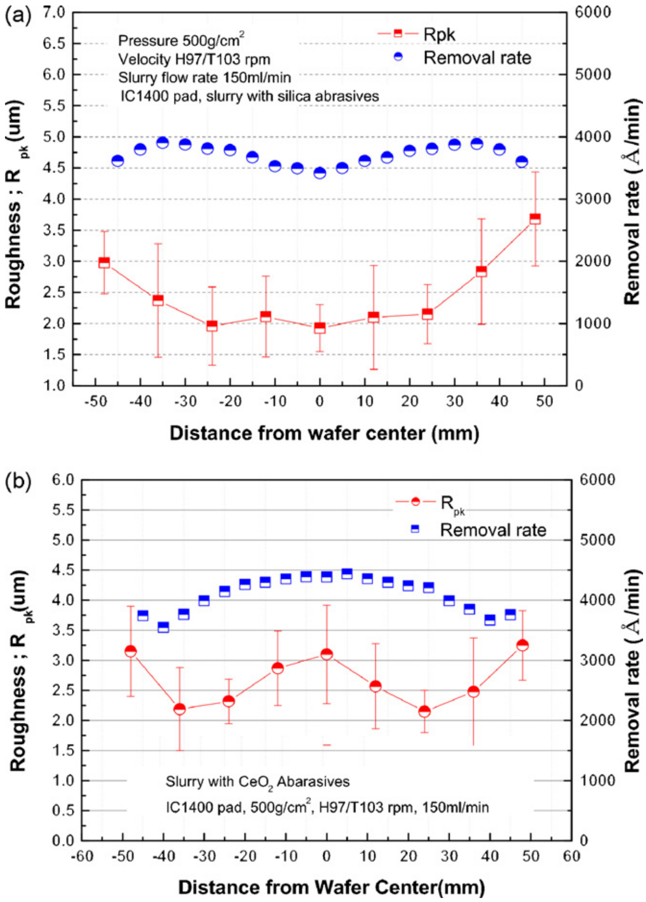

Fig. 5 – Profile of pad surface roughness and removal rate as a function of distance from wafer center. (a) Silica-based slurry. (b) Ceria-based slurry.

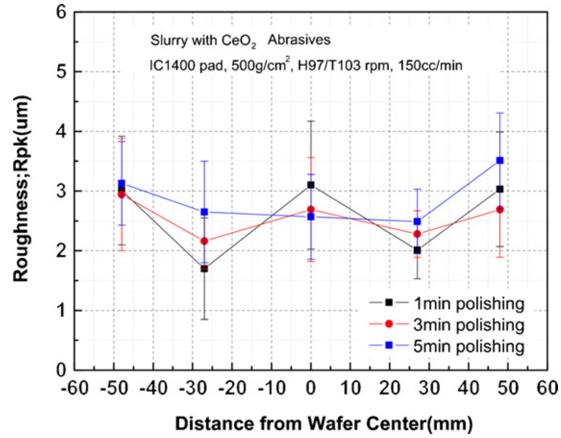

Fig. 6 – Temporal variation of roughness distribution as a function of polishing time.

tion of surface roughness was satisfied with investigation on spatial roughness change after oxide CMP using two slurries.

The oxide wafer was polished using silica-based slurry and the R_{pk} of pad surface roughness was measured after CMP of one minute. Fig. 5(a) shows the correlation between the removal rate profile and the variation of deteriorated surface roughness. The stylus tester scanned nine points at each direction of 0°, 90°, 180°, and 270°across the apparent contact area of the pad, and the measured R_{pk} are its average value and its deviation. The removal rate profile across the whole wafer typically had a lower removal rate in the wafer center than on its edge. It is known as edge effect where the removal rate of around ±35 mm from wafer center is higher because of the stress concentration in the pressured wafer i.e. the pad rebound phenomenon (Wang et al., 1997). In particular, the shape of pad roughness after CMP was more concave than it was after the conditioning process. This was due to the degradation of pad roughness according to sliding distance distribution. The average values of the R_{pk} parameter after CMP and after conditioning were 2.3 μm and 2.4 μm each, so they were very similar. The R_{pk} of surface roughness generally decreases, as the polishing time increases without in situ conditioning. Park (Park et al., 2007) revealed that the roughness R_{pk} dramatically decreased according to the polishing time without the conditioning process. However, CMP process should finish in about one minute for throughput. Therefore the shape of roughness distribution is more important than the average R_{pk} of total measured roughness values.

3.3. *Pad roughness variation and removal rate profile of ceria-based slurry*

Fig. 5(b) shows that the removal rate using ceria-based slurry was higher in the wafer center than that of using silica-based slurry. It is well known as the center fast aspect of material removal rate. The R_{pk} value of roughness parameters increased around the contact area center between pad and wafer after CMP process, in comparison to its shape after conditioning. The ceria abrasives might have an effect on the convex shape of pad roughness. The average value of R_{pk} was also 2.7 μm which was higher than that before CMP. Cook (1990) proposed that the polishing mechanism was the chemical condensation reaction between ceria abrasive and oxide film i.e. chemical tooth effect. Hoshino (Hoshino et al., 2001) also proposed that the oxide film was removed as ceria abrasives with SiO_2 lump during polishing. Therefore, the slurry accumulation in the wafer center can be predicted during CMP. Also, another reason is that the specific gravity of dispersed ceria abrasives is higher than that of silica abrasives. In CMP process, the slurry is supplied around the pad center and then sucked into the wafer, followed by being discharged out of the pad. Thus, ceria abrasives can be chemically fixed on the SiO_2 film of the wafer center because of chemical tooth effect, which results in the accumulation of more abrasives. The wafer surface, with abrasives, can scrub the pad surface during CMP, hence we assumed that the pad surface roughness increased and the removal rate in the wafer center was higher.

Fig. 6 shows the result of investigating the temporal variation of pad roughness. The distribution shape of pad roughness was transformed into smooth and concave surface, as polishing time increased from 1 min to 5 min. The average values of R_{pk} went up to 2.8 μm after 5 min. The results describe the temporal formation of pad roughness with spa-

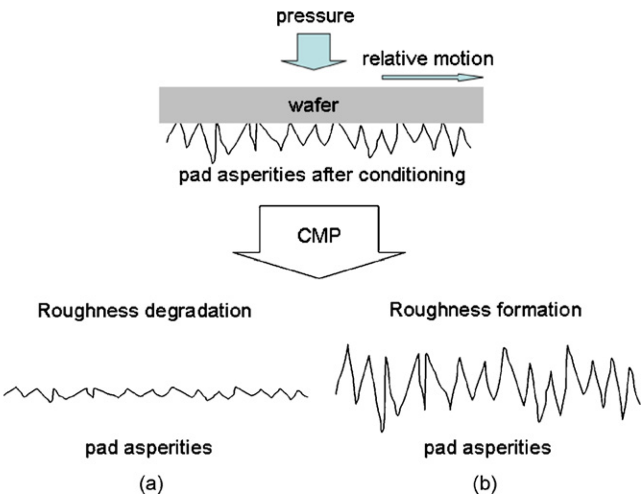

Fig. 7 – Schematic of pad roughness change during CMP. (a) Silica-based slurry. (b) Ceria-based slurry.

tial distribution. Therefore, Fig. 7 shows the schematics of pad roughness change during CMP process using two types of slurry.

The friction signals were measured using both silica-based slurry, and ceria-based slurry in oxide CMP. Fig. 8(a) shows that the friction force decreases during polishing, in the case of silica-based slurry, because of the viscoelastic behavior of the pad, pad deformation, and the degradation of pad roughness. The friction force also reflects the amount of material removal in oxide CMP (Jeong et al., 2004; Park et al., 2007; Kim et al., 2002). By contrast, the average friction force increased during polishing using ceria-based slurry as shown in Fig. 8(b). This means that the spatial formation of pad surface roughness may have happened and the contact condition between pad and wafer can be unstable during CMP, which results in the equipment vibrating.

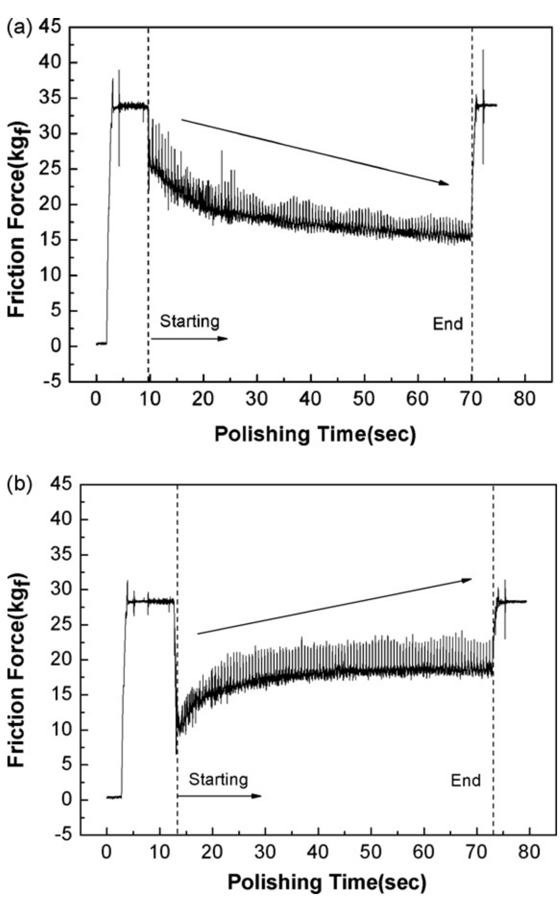

Fig. 8 – Friction force as a function of polishing time. (a) Silica-based slurry. (b) Ceria-based slurry.

The proposed model for roughness formation can make the removal rate profile become convex in oxide CMP using ceria-based slurry. As a solution to this problem, an industry can control the process parameters such as adjustment of slurry pH and viscosity, pressure and velocity of CMP equipment carrier, and in situ conditioning. The viscosity adjustment of parameters was interpreted as being a more effective method for improvement of removal rate profile. We especially believe that higher viscosity slurry with organic surfactant as additive can prevent the ceria abrasives to roughen the pad surface even though the oxide removal rate goes down because of it (Lim et al., 2005; Kang et al., 2004; Doi, 2007).

4. Conclusions

The oxide CMP process using ceria-based slurry has a problem: a higher material removal rate in wafer center, compared with CMP using silica-based slurry. So, this research includes the effects of pad roughness on the material removal profile. The R_{pk} distribution of pad roughness has a concave shape in conventional silica-based CMP slurry because of pad wear. However, the ceria-based slurry forms the pad roughness, which results in a high removal rate in the wafer center. Therefore, the ceria abrasives affect the spatial and temporal distribution of pad roughness. It is expected that the chemical tooth effect between oxide film and ceria abrasive, and the slurry accumulation in the wafer center will roughen the pad surface. The characteristic of ceria abrasive must be considered for improvement of within wafer non-uniformity.

Acknowledgement

This work was supported by a grant-in-aid for the National Core Research Center Program from the Ministry of Science & Technology and the Korea Science & Engineering Foundation (No. R15-2006-022-01003-0).

REFERENCES

Chang, O., Kim, H., Park, K., Park, B., Seo, H., Jeong, H., 2007. Mathematical modeling of CMP conditioning process. Microelectron. Eng. 84, 577–583.

Cook, L., 1990. Chemical processes in glass polishing. J. Non-Crystal. Solids 120, 152–171.

Doi, T., 2007. Chemical mechanical polishing and its applications. In: Marinescu, L., Uhlmann, E., Doi, T. (Eds.), Handbook of Lapping and Polishing. CRC Press, Boca Raton.

Hooper, B.J., Byrne, G., Galligan, S., 2002. Pad conditioning in chemical mechanical polishing. J. Mater. Process. Technol. 123, 107–113.

Hoshino, T., Kurata, Y., Terasaki, Y., Susa, K., 2001. Mechanism of polishing SiO_2 films by CeO_2 particles. J. Non-Crystal. Solids 283, 129–136.

Jeong, H., Park, B., Lee, H., Kim, H., Seo, H., Kim, G., Park, K., Kinoshita, M., Park, J., 2004. Monitoring system in CMP process. In: Proc. The 1st Pac-Rim International Conf. on Planarization CMP and Its Application Technology, Tokyo, 6 December, pp. 57–68.

Jin, X., Keer, L.M., Wang, Q., 2005. A 3D EHL simulation of CMP. J. Electrochem. Soc. 152, G7–G15.

Kang, H., Katoh, T., Lee, M., Park, H., Paik, U., Park, J., 2004. Effect of molecular weight of surfactant in nano ceria slurry on shallow trench isolation chemical mechanical polishing (CMP). Jpn J. Appl. Phys. 43 (8B), L1060–L1063.

Kim, H.J., Kim, H.Y., Jeong, H.D., Lee, E.S., Shin, Y.J., 2002. Friction and thermal phenomena in chemical mechanical polishing. J. Mater. Process. Technol. 130–131, 334–338.

Lee, S., Hwang, J., Kim, H., Jeong, H., 2007. Investigation of polishing characteristics of shallow trench isolation chemical mechanical planarization with different types of slurries. Microelectron. Eng. 84, 626–630.

Lim, J., Yun, S., Lee, J., Yoon, B.U., Hong, C., Cho, H., Moon, J., 2005. Effect of ceria slurry pH and Hersey number on CMP of silicon dioxide. In: Proc. CMP for ULSI Multilevel Interconnection Conf. Fremont, 23–25 February, pp. 488–493.

MaGrath, J., Davis, C., 2004. Polishing pad surface characterization in chemical mechanical planarization. J. Mater. Process. Technol. 153–154, 666–673.

Oliver, M.R., 2004. Chemical-mechanical planarization of semiconductor materials. Springer, Berlin Heidelberg.

Oliver, M.R., Schmidt, R.E., Robinson, M., 2000. CMP pad surface roughness and CMP removal rate. In: Proc. Electrochemical Society 198th Meeting, Phoenix, 22–27 October, p. 77.

Park, K.H., Kim, H.J., Chang, O.M., Jeong, H.D., 2007. Effects of pad properties on material removal in chemical mechanical polishing. J. Mater. Process. Technol. 187–188, 73–76.

Qin, K., Moudgil, B., Park, C.W., 2004. A chemical mechanical polishing model incorporating both the chemical and mechanical effects. Thin Solid Films 446, 277–286.

Scott Lawing, A., 2002. Pad conditioning and pad surface characterization in oxide chemical mechanical polishing. In: Proc. Materials Research Society Spring Meeting, San Francisco, 1–5 April, pp. I5.3.1–I5.3.6.

Tomozawa, M., 1997. Oxide CMP mechanisms. Solid State Technol., 169–175.

Wang, D., Lee, J., Holland, K., Bibby, T., Beaudoin, S., Cale, T., 1997. Von Mises stress in chemical–mechanical polishing process. J. Electrochem. Soc. 144 (3), 1121–1127.

Yoshida, T., 2004. Pad asperity parameters for CMP process simulation. In: Proc. Materials Research Society Spring Meeting, San Francisco, 12–16 April, pp. K.8.4.1–K.8.4.6.